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EFFECTS OF FIRE ON STRUCTURE AND COMPOSITION OF VEGETATION COMMUNITY IN PINE FORESTS, NAM NAO NATIONAL PARK, THAILAND**

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Running title: Fire effects on vegetation in pine forests, Thailand

ABSTRACT

Anthropogenic forest fires have been widely reported in many forests of Thailand, including pine forests. Although pine forests are fire dependent, too frequent burning could affect nutrient depletion and ecosystem degradation. This study aimed to examine the effects of forest fire on the structure and composition of vegetation community in a degraded pine forest (PF) and in a mixed pine-oak forest (O-PF) of Phu Kum Khao, Nam Nao National Park, Phetchabun Province. The effects of fire in one year were studied using three 50x50 m experimental plots established in each forest type. Results demonstrated that fire caused significantly higher tree mortality rate in the degraded pine forest than in the mixed pine-oak forest. In addition, it was found that the seedling ratio of vegetation in the mixed pine-oak forest was more than in the degraded pine forest. Furthermore, there was no significant effect of burning on sapling and seedling density, diameter and height. This insignificant difference could be due to the high variation of fire behavior in each plot. The study also found that sapling and seedling diameters were slightly different. Since the effects of forest fire could be a potential parameter causing forest degradation in the study area, further studies on effects of fire frequency on vegetation structure and composition should be conducted to provide sufficient measures, support efficient forest fire management, and prevent further ecosystem degradation.

Keywords: burning, degraded pine forest, Nam Nao National Park, pine-mixed oak forest

INTRODUCTION

Forest fire is a critical factor shaping ecosystem structure in many forest areas (Pyne, 2001). It has, however, been reported that too frequent forest fires have caused ecosystem degradation in many areas including tropical pine forests (Goldammer & Penafiel 1990, Wanthongchai and Goldammer, 2011). Given the flammable forest floor which mainly consisting of grasses and pine needles, and frequent anthropogenic burning activities such as agricultural residual burning around the forest, pine forests of Phu Kum Khao, Nam Nao National Park experience forest fires almost every year (Tarusadamrongdet, 2013). Physical characters of pine trees such as thick bark and well-protected buds by clumped needles make them resistant to fires (Kutintara, 2008; Brown & Smith, 2000). A preliminary survey in this area, however, showed that the plant community was dominated by widely scattered large pine trees as the top forest canopy, while there is no other species in the lower canopy layer. In addition, the forest floor was covered by dense grasses. This preliminary finding suggested limitation to natural regeneration. This forest structure could be associated with annual forest fires. Furthermore, evidences of other external pressures causing plant mortality and degradation were found in this forest area, such as lightning and pine resin collection. Forest fires, natural mortality and anthophogenic pressures negatively impact natural regeneration process and nutrient cycling which could eventually cause forest degradation. If this situation persists for long without proper management, the pine forest community might be replaced by savanna ecosystem (Cochrane, 2009).

Although pine forests are fire dependent ecosystems, the fire resistant ability of the vegetation depends on suitable burning regimes. In other words, the fire frequency, fire intensity and burning area, which are critical factors determining the presence of pine trees in the ecosystem must be compatible with the ecological and biological processes of the plant community (Cochrane, 2009).

This study aimed to examine effects of fire on vegetation structure and composition, and natural regeneration within one year after burning in a degraded pine forest and a mixed oak-pine forest of Phu Kum Khao, Nam Nao National Park (Figure 1).

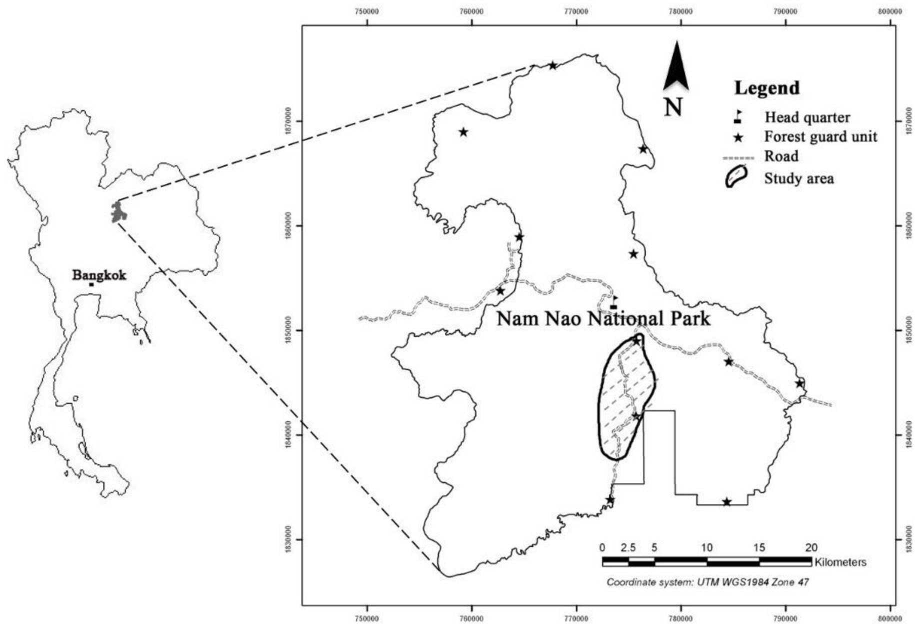

Figure 1 Location of Nam Nao National Park and Study Area

MATERIALS AND METHODS

A degraded pine forest (PF) (referred to savanna-like community, which most of the areas covered by grass with very few pine trees) and a mixed oak-pine forest (O-PF) in Phu Kum Khao, Nam Nao National Park, Phetchabun province were chosen for this study. These communities were classified by Kutintara (2008). Three 50x50 m experimental plots were set up in each forest type. Within each plot, there were four 25x25 m sub-plots. Fire breaks were constructed around all the experiment plots (Figure 2).

Structure and composition of trees (DBH > 4.5 cm) were examined in each sub-plot. DBH and height of tree were recorded. In each sub-plot, 4x4 m and 2x2 m plots were established for sapling and seedling measurement, respectively (Figure 2). Diameter at trunk base (D_0), DBH and height were recorded for all saplings and seedlings. Individual canopy area and height of burning scar at the tree trunk were also measured. Crown cover of the vegetation community was photographed using a digital camera with 18 mm fish eye lens. The camera was set at 1 m from the ground.

Burning experiments with head fire burning technique were conducted in March 2012 by the fire control officers of Petchabun Province. Prior to burning, firebreak was setup and ignition point was start based on wind direction. Species and number of trees (woody plant that has dbh>4.5 cm), saplings (woody plant that has dbh<4.5 cm, height>1.30 m), seedlings (woody plant that has height<1.30 m) and ground flora (herbaceous, grass and climber) were re-examined 12 months after burning. Fuel characteristics and fire behaviors during burning experiment have been conducted and reported by Wanthongchai *et al.* (2013)

Crown cover was calculated using Hemiview version 2.1 program. Vegetation density, basal area, diameter class distribution, and Shannon-Weiner Diversity Index were calculated (Wanthongchai *et al*. 2014). Effects of fire on structure and composition of plant community were compared i) between degraded pine forest and mixed oak-pine forest, and ii) before and after burning in each community, at the 95% confidential level.

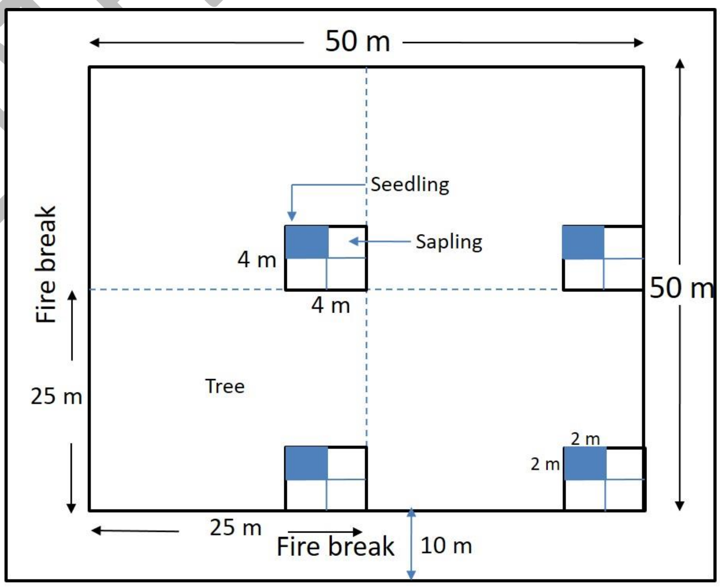

Figure 2 Plot layout for vegetation measurement.

RESULTS AND DISCUSSION

Structure of plant community before the burning experiment

Before burning experiment, 30 and 25 tree species were found in the PF and the O-PF, respectively. Disturbance regime that degraded pine has been burned may result in higher number of species. Vertical structure of vegetation in the PF consisted of 2 canopy layers. The dominant trees were *Pinus kesiya* with height over 30 m, and widely scattered in the study area. The second dominant species were hill evergreen tree species with height less than 10 m, such as *Craibiodendron stellatum* and *Terminalia chebula*. On the other hand, vertical structure of O-PF consisted of 3 canopy layers. *P. kesiya* more than 30 m height dominated the top canopy. The middle canopy species were *Lithocarpus grandifolius, Quercus auricoma, Dipterocarpus obtusifolius and Aporosa villosa* with height about 15-20 m. The lower canopy included the smaller trees of the top and medium canopy and some other small tree such as *Phyllanthus emblica*, *Ardenia sootepensis* and *Memecylon scutellatum*. Tree density in PF was 304 trees/ha, while O-PF had four times higher tree density (Table 1). Seedling density in the PF were lower than in the mixed oak-pine forest. Percent canopy cover of saplings in the degraded pine forest (37.45%) were slightly higher than in the mixed oak-pine forest (31.48%). The higher percent canopy cover of sapling and lower seedling density could be due to the annual fire disturbance.

Pre-burning survey of species diversity found a total of 47 tree species in these study plots. Number of tree species was higher in the PF than in the O-PF. Regarding Shannon-Wiener Index of saplings and seedlings which is an indicator of natural reproduction, the results showed similar number in both forests.

Table 1 Pre-burn vegetation structure and composition in the degraded pine forest (PF) and the mixed oak-pine forest (O-PF), Phu Kum Khao, Nam Nao National Park.

	Structure [a]	PF	O-PF
Tree	Density (indiv./ha)	304^{a} (43.5)	1327^{b} (242.4)
	Basal area (m^2/ ha)	11.1^{a} (0.53)	17.4^{b} (1.96)
	Canopy area (m^2/ ha)	5943.1^{a} (630.16)	12450.6^{b} (1210.14)
	Number of species	30	25
	Shannon-Wiener Index (H)	2.808	2.083
Sapling	Density (indiv./ha)	6667^{a} (1458.3)	4583^{a} (1102.4)
	Diameter at Trunk Base: D_0 (cm)	2.45^{a} (0.34)	2.38^{a} (0.89)
	Diameter at Breast Height : DBH (cm)	0.97^{a} (.26)	1.23^{a} (0.41)
	Height (m)	1.87^{a} (0.17)	1.98^{a} (0.28)
	Canopy cover (%)	37.45^{a} (4.48)	31.48^{a} (11.30)
	Number of species	11	13

	Shannon-Wiener Index (H)	2.217	2.39
Seedling	Density (indiv./ha)	50833^{a} (16729.2)	70833^{a} (16414.8)
	Diameter at Trunk Base D_0 (cm.)	0.50^{a} (0.04)	0.44^{a} (0.13)
	Height (m)	0.52^{a} (0.05)	0.36^{a} (0.04)
	Canopy cover (%)	20.79^{a} (11.13)	44.52^{a} (16.14)
	Number of species	22	19
	Shannon-Wiener Index (H)	2.829	2.436

^{a} Different superscript letters (a, b) indicate significant differences (*t*-test, $P < 0.05$) of vegetation structures in the two forest types. Standard deviation values are presented in the parentheses.

Effects of burning on structure and composition of plant community

Effects of fire on tree mortality and density

The data collected one-year after the burning experiment showed that mortality rates of trees in PF (4.59%) and O-PF (1.15%) were significantly different ($p< 0.05$). The tree species that died after the fire in the O-PF were *Q. auricoma*, *D. obtusifolius* , *G. sootepensis* and *P. kesiya.* The tree species died after the fire in the PF consisted of *C. stellatum*, *Pterocarpus macrocarpus*, *Albizia odoratissima*, *S. wallichii*, *Protium serratum* and *P. kesiya.* It was noted that *D. obtusifolius* which died after burning had smaller diameter than the average diameter of the same species.

Although the burning caused mortality in some species in the experimental plots, average tree densities in the PF before and after the burning experiment were not significantly different (p=0.07). In contrast, the tree density in the O-PF before and after the fire were significantly different ($p<0.05$), and reduced from 1327 to 1313 indiv./ha (Table 2). This result may reflect the fact that tree species in degraded forest, where burnings frequently occur, adapted to fire environment and therefore can tolerate in the ecosystem.

Table 2 Tree (DBH > 4.5 cm) density before the burning experiment and one year after the burning experiment.

Plot	Tree Density (indiv./ha)^{a}		
	Pre-burning	Post-Burning	Mortality (%)
PF-1	375	356.25	5.00
PF-2	312.5	293.75	6.00
PF-3	225	218.75	2.78
average-PF	304.2^{a} (43.5)	289.6^{a} (39.7)	4.59^{a} (0.95)
O-PF-1	1662.5	1643.75	1.13
O-PF-2	856.25	843.75	1.46
O-PF-3	1462.5	1450	0.85
average-O-PF	1327.1^{a} (242.4)	1312.5^{b} (240.9)	1.15^{b}(0.18)

^{a} Different superscript letters (a, b) indicate significant differences (*t*-test, $P < 0.05$) of tree density before and after the burning experiments in each of the forest types. Standard deviation values are presented in the parentheses

Effects of fire on density, diameter and height of saplings and seedlings

A comparison of density changes showed that sapling density in the PF decreased more than in the O-PF after the fire. The saplings that survived after the burning experiment tended to be taller and larger in diameter than the saplings before the fire. The averaged DBHs range was 0.6-2.4 cm and height range was 1.5-2.4 m. The statistical analysis suggested that fire did not show significant effect on vegetation structures of saplings in this study (Table 3). The estimated diameter and height growth rates were 0.4-0.8 cm/year, and 0.2-0.4 m/year, respectively.

It was found that the density per area and canopy area of seedlings after burning were higher in both degraded pine forest and mixed oak-pine forest, while the diameter at trunk base and height of seedlings were lower. A statistical analysis suggested that only seedling height in the mixed oak-pine forest significantly decreased after the fire (p<0.05). On the other hand, there was no significant difference among all other parameters. The high fire variations during the burning experiment could account for the insignificant difference. The lower height of seedlings could be due to a replacement by new seedlings after the fire.

Table 3 Structure of saplings and seedlings in the degraded pine forest (PF) and the mixed oak-pine forest (O-PF), Phu Kum Khao, Nam Nao National Park, before and after the burning experiment.

	Structure [a]	PF		O-PF	
		Pre-burn	Post-burn	Pre-burn	Post-burn
Sapling	Density (indiv./ha)	6666.7^{a} (1458.3)	2500.0^{a} (360.8)	4583.3^{a} (1102.4)	3541.7^{a} (1041.7)
	Diameter at trunk base: D_0 (cm)	2.45^{a} (0.34)	2.23^{a} (0.55)	2.38^{a} (0.89)	3.00^{a} (0.72)
	Diameter at Breast Height: DBH (cm)	0.97^{a} (0.26)	1.00^{a} (0.25)	1.23^{a} (0.41)	1.67^{a} (0.54)
	Height (m)	1.87^{a} (0.17)	2.13^{a} (0.09)	1.98^{a} (0.28)	1.90^{a} (0.26)
	Canopy cover (%)	37.45^{a} (4.48)	28.57^{a} (7.05)	31.48^{a} (11.30)	31.72^{a} (14.73)
Seedling	Density (indiv./ha)	50833.3^{a} (16729.0)	74166.7^{a} (20531.1)	70833.3^{a} (16414.8)	79166.7^{a} (14529.7)
	Diameter at trunk base:D_0 (cm)	0.50^{a} (0.04)	0.48^{a} (0.05)	0.44^{a} (0.13)	0.34^{a} (0.07)
	Height:Ht (m)	0.52^{a} (0.05)	0.38^{a} (0.01)	0.36^{a} (0.04)	0.28^{b} (0.05)
	Canopy cover (%)	20.79^{a} (11.13)	72.18^{a} (20.18)	44.52^{a} (6.15)	49.32^{a} (10.90)

[a] Different superscript letters (a, b) indicate significant differences (t-test, P < 0.05) of sapling and seedling structures before and after the burning experiments in each of the forest types. Standard deviation values are presented in the parentheses.

Variation of diameter classes of saplings and seedlings

The results showed that number of post-burn saplings in each diameter class in the PF was lower than before the burning experiment. There were no saplings in the large diameter class in the PF site both pre- and post- burning (Figure 3a). On the other hand, no clear pattern was found in the O-PF as the number of post-burn saplings in small diameter class (1.1-3.0 cm) was lower than those of pre-burn, while the number in several other diameter classes, particularly in the medium diameter class (3.1-7.0 cm), was larger after burning. These increases could be attributed to the low fire intensity which did not cause sapling mortality (Figure 3b).

The study of seedlings demonstrated that the seedling distribution was spread to more class sizes in both the PF (Figure 3c) and the O-PF (Figure 3d). In the O-PF, number of seedling in smaller diameter-classes were more than that in the larger diameter-classes. Overall, the average number of seedlings in the O-PF were lower after the burning experiments except diameter class 0.3-0.6 cm (Figure 3d). In the PF, number of seedlings in the small and medium diameter classes after the burning experiments were more than before burning. The disappearance of grass just after the fire might be accounted for by forest floor opening and hence stimulating new seedling recruitment. Nevertheless, if the fires repeat in the following year, these seedlings could be destroyed by the subsequent burning.

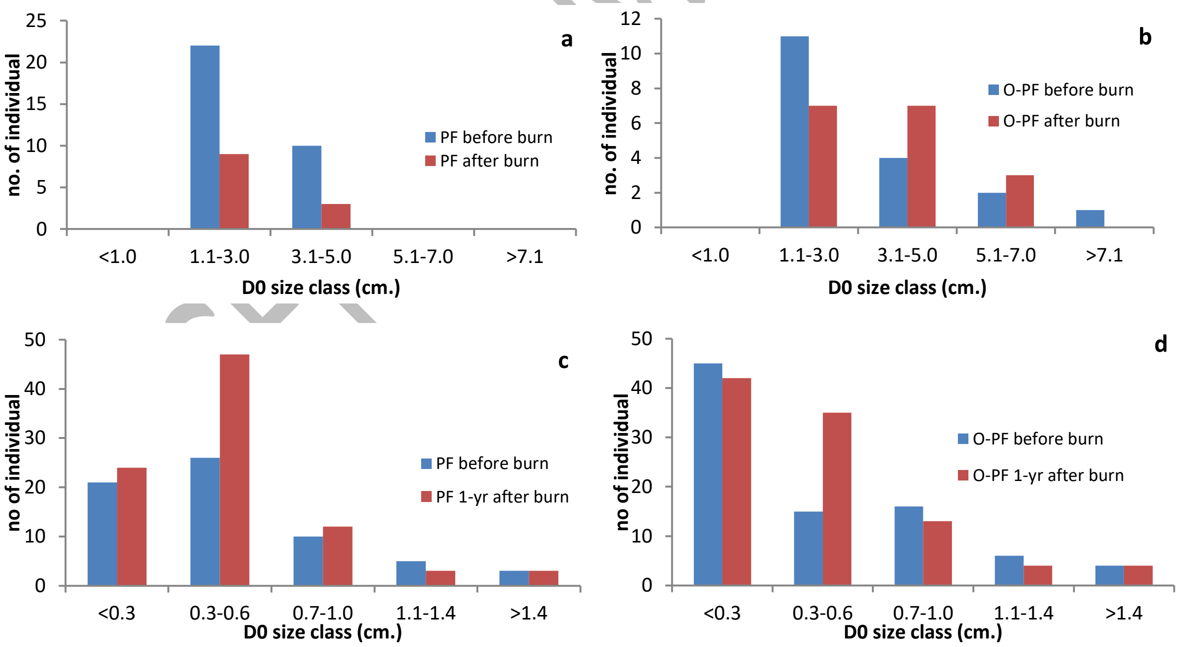

Figure 3 Distribution of saplings in different diameter classes at trunk base (D_0) before and after the burning experiment in the degraded pine forest (PF) (a) and the mixed oak-pine forest (O-PF) (b), and distribution of seedlings in different diameter classes before and after the burning experiment in the degraded pine forest (PF) (c) and the mixed oak-pine forest (O-PF) (d).

Seedling ratio

Rapid coppicing ability is one of critical characters which enable plants to adapt to the fire conditions. Coppicing ability is measured by comparing the proportion of total number of new sprout and number of seedling stumps in the experimental plots. This proportion is called seedling ratio. High seedling ratio indicates that the plants have high coppicing potential. From this study, the seedling ratios in the PF and O-PF forests before burning were 1.1 and 2.5, respectively. Changes in seedling ratio after the fire for both study sites, however, were not significantly different (Figure 4)

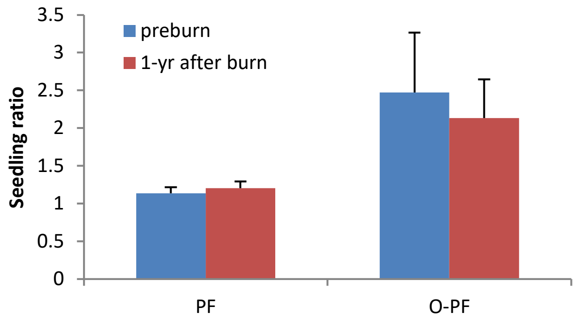

Figure 4 Seedling ratios of the vegetation before and after the burning experiments in the degraded pine forest (PF) and the mixed oak-pine forest (O-PF). Error bars represent standard deviation.

Pine forests are fire dependent ecosystems. Fire regime, which consists of fire types, fire frequency, fire intensity, fire season and burned area (Chandler *et al.*, 1983), is a critical factor affecting growth process, development and natural regeneration of trees in pine forests (Kutintara, 2008). This study, in particular, demonstrated that fire had different impacts on the plant communities in the degraded forest and in the mixed oak-pine forest.

Effects of fire in each burning experiment

Most of the forest fires in pine forests of Thailand affect saplings and seedlings more than large trees as the fires usually burn only surface fuel with low to medium fire intensity. Wanthongchai, *et al.* (2013) reported that fire behavior characteristics in the PF stand were significantly greater than those in the O-PF stand. Burning at the O-PF and the PF were classified as low-intensity (48 kW/m), and medium-intensity (627 kW/m), respectively (Table 4). During the burning experiment, the surface soil temperatures at all sites were higher than 250 °C. However, fire did not cause temperature changes in the deeper soil layers. Several tree species in the study area were resistant to the fire because of their physical characteristics such as thick bark and fast coppicing ability. Nevertheless, these characteristics are not usually developed in the sapling and seedling stages, but are likely to show when they attain mature growth stages. Therefore, the fire resistant ability and capability have positive correlation with tree age (Whelan, 1995).

The ratio of the number of newly sprouted shoots, or suckers, to the number of individual seedlings (seedling ratio) was even more interesting. It was found that seedling ratios in the PF were lower than the ratios in the O-PF. One explanation could be that the more frequent burning in the PF activates more frequent tree coppicing which consumes the stored energy. Therefore, this reduction of stored energy could result in the reduction of seedling ratio in the subsequent fire (Wanthongchai 2008). On the other hand, the forest fire in the O-PF was less than that in the PF, which saved more stored energy for coppicing as a result of higher seedling ratio. There is concern that if the fire events remain too frequent, the coppicing ability for many seedlings will decrease and eventually die. Wanthongchai (2008) reported that the capacity for the vegetative propagation (as indicated by ratio of sprout to individuals) of seedlings increased on the less frequently burned sites after the burning experiment in the dry dipterocarp forest. On the site that burned too frequently, by contrast, the number of sprouts decreased after the fire.

Table 4 Quantitative average fire behavior characteristics, flame temperature and soil temperature in degraded pine forest (PF) and pine-oak forest (O-PF) [a]. Standard errors are given in parentheses.

Fire characteristic [b]	Stand	
	PF	O-PF
Head-fire rate of spread (m/min)	4.5^{a} (±1.0)	0.9^{b} (±0.2)
Back-fire rate of spread (m/min)	0.8^{a} (±0.1)	0.3^{b} (±0.1)
Average flank-fire rate of spread (m/min)	1.2^{a} (±0.2)	0.5^{b} (±0.01)
Head-fire flame height (m)	2.5^{a} (±0.2)	0.6^{b} (±0.04)
Back-fire flame height (m)	1.2^{a} (±0.3)	0.2^{b} (±0.1)
Average flank-fire flame height (m)	0.6^{a} (±0.03)	0.2^{b} (±0.1)
Flame length (m)	1.4^{a} (±0.1)	0.4^{b} (±0.1)
Fireline intensity (kW/m)	626.6^{a} (±129.9)	47.9^{b} (±23.0)
Heat release per unit area (kJ/m)	288.6^{a} (±22.9)	85.8^{b} (±40.7)
Flame temperature (°C)		
20 cm aboveground	586.5^{a} (±29.1)	389.7^{b} (±55.8)
50 cm aboveground	471.6^{a} (±45.6)	301.2^{a} (±64.5)
Maximum soil temperature (°C)		
soil surface	484.9^{a} (±146.6)	255.2^{a} (±105.4)
2 cm beneath the soil surface	24.1^{a} (±1.3)	25.9^{a} (±0.1)
5 cm beneath the soil surface	20.2^{a} (±0.1)	23.6^{b} (±0.3)
10 cm beneath the soil surface	19.2^{a} (±0.3)	21.7^{b} (±0.2)

[a] Wanthongchai *et al.* (2013)
[b] Different superscript letters (a, b) indicate significant differences (*t*-test, $P < 0.05$) in the average fire behavior characteristics, flame temperature and soil temperature between degraded pine forest and pine-oak forest. Flame length and fireline intensity were calculated using Byram's formula (Byram 1959).

This study showed that there was about 5% and 1% of tree mortality in the PF and the O-PF, respectively. Tree mortality could be used as an indicator of fire intensity. Higher mortality in the degraded pine forest could imply higher fire intensity as the dense grass covering the forest floor was highly inflammable. It is predicted that more frequent fire events in the degraded pine forest could prevent natural regeneration and therefore lead to potential replacement of pine forest by savanna ecosystem. Therefore, effective forest fire management that only allows the fire to take place occasionally is critical for the conservation and restoration of this degraded pine forest. The “fire-free period” must be allowed long enough for natural regeneration to take place. For example, Wanthongchai *et al.* (2008) found that the appropriate burning frequency to maintain vegetation structure and site fertility in dry dipterocarp forest was 2-3 times per decade.

It was also noted that mortality was found in fire resistant species such as *P. kesiya* and *D. obtusifolius*. The death of these species was likely caused by natural inter-tree competition rather than from the fire. This hypothesis needs to be verified with further experiments as this study did not have control plots. Also, due to lack of control plots, no conclusions could be made from this study regarding effects of fire on tree growth rate.

This study showed that fire caused a decrease in the number of saplings in both degraded pine forest and mixed oak-pine forest. The number of saplings in the degraded pine forest decreased more than in the mixed oak-pine forest. This could be explained by fire intensity. Wanthongchai *et al.* (2013) previously reported that fire intensity and flame height in the degraded pine forest (627 kW/m and 1.4 m) was higher than in the mixed oak-pine forest (48 kW/m and 0.4 m). This higher fire intensity in the degraded pine forest could also account for the decrease in diameter of saplings in all the diameter classes. On the other hand, the low fire intensity in the mixed oak-pine forest could explain the increase in diameter of saplings in larger diameter classes as the fire intensity was not high enough to kill the saplings but to stimulate their growth. It should be noted that the decrease in the number of saplings did not always imply the sapling mortality as the new shoots grew but their sizes were not big enough to be considered as saplings. This observation could also explain the decrease in height of saplings. For seedlings, both diameter-class distribution and numbers were higher after the fire. This could be due to the grass mortality from fire, which provides seedbed for seedlings to germinate and grow. Note, however, that if a subsequence fire occurs in the following year, these seedlings could be killed by the fire.

Effects of burning regimes

Fire frequency is one of the major burning regime factors that greatly affects plant community structure and composition. Excess fire frequency in natural occurrence will likely cause ecosystem degradation (Kimmins, 1997). This situation is more commonly found in degraded pine forests than in mixed oak-pine forests. Degraded pine forests are also described as composed of scattered big trees, and low sapling and seedlings density, due to tall grass domination. Wanthongchai *et al.* (2013) reported that the main fuel proportion in the PF stand was grass (45%) and litter (44%), whereas leaf litter was the most important fuel in the O-PF stands (55%). In the dry season, these grasses and litter dry up and become flammable fuel and intensify forest fire, which destroys the trees, saplings and seedlings. This situation would further open up the space for fast growing grasses and weeds, especially xerophytic species, to grow and, hence, ready to ignite. If this grass-fire cycle persists, the degraded pine forest will eventually be succeeded by savanna grassland (Whelan, 1995). This ecosystem succession process mentioned above was also observed in the degraded pine forest of Phu Kum Khao in this study.

High fire frequency and intensity could also interfere with the natural regeneration process as they cause mortality in saplings and seedlings. In particular, in the degraded pine forest of this study, *P. kesiya* grew very tall and continuously got struck and killed by lightning. This factor will also contribute to ecosystem succession by savanna grassland. Therefore, immediate fire protection and management are needed to assist the natural regeneration and allow pine seedling and saplings to grow since they need time to adapt in the fire environment (Royal Forest Department, 2008). In addition, as the degraded pine forest floor is dominated by grass that prevent seedlings from germinating and growing, it is also important to eliminate the grass and weeds. Long term fire management to secure natural regeneration (seedlings and saplings) will also be critical. It is suggested that suitable fire frequency which will allow the natural reproduction should be further studied. Wanthongchai *et al.* (2013) found that the post-burn fuel loads one year after the fire in the degraded pine forests were still lower than the pre-burn level. These results may imply that a degraded pine forest at Nam Nao National Park requires more than one year of fire-free period to recover back to the pre-burn conditions.

CONCLUSION

The study of effects of fire on vegetation structure and composition in the degraded pine forest and the mixed oak-pine forest of Phu Kum Khao, Nam Nao National Park suggested that fire significantly caused higher tree mortality in the degraded pine forest than in the mixed oak-pine forest. The fire effects on natural regeneration density, diameter and height was, however, not clearly demonstrated in this study. This could be due to the high variation of fire behaviour in each experimental plot. On the other hand, the number of seedlings increased after the burning experiment due to more open space for the seeds to germinate and grow. Diameter of seedlings and saplings were only slightly different while seedling ratios in the mixed oak-pine forest was more than in the degraded pine forest. Effects of fire frequency on vegetation structure and composition should be conducted since it is a critical factor contributing to future forest degradation.

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